

Modern Diesel Technology

Mobile Equipment Hydraulics: A Systems and Troubleshooting Approach

Ben Watson



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CHAPTER

1

An Overview

Learning Objectives

Upon completion and review of this chapter, the student should be able to:

- Describe fluid flow through a typical cylinder-based hydraulic system.
- Describe fluid flow through a typical motor-based hydraulic system.
- Predict how pressure changes as fluid flows through a typical hydraulic system.
- Predict how temperature changes as fluid flows through a typical hydraulic system.
- Predict which components in a typical hydraulic system can affect flow.
- Predict where and how velocity will change in a typical hydraulic system.
- Describe how changes in pressure cause changes in force.
- Describe how changes in flow rate cause changes in the speed of operation in a system.

Cautions for This Chapter

- When inspecting a system, remember that the hydraulic fluid may be under high pressure.
- When working around a system with leaks, remember that hydraulic oil on the floor can be extremely slippery.
- Remember that when hydraulic fluid is under high pressure and when escaping under high pressure through a small leak, that leak may be invisible.
- Remember that when hydraulic fluid is under high pressure and escaping through a small leak, the escaping high-pressure fluid can penetrate the skin. Injected hydraulic fluid is toxic.
- Remember that hydraulic systems are designed to move large and heavy loads. These loads can be dangerous should they move or shift unexpectedly.
- ALWAYS wear safety glasses.

Key Terms

area	force	Occupational Safety and Health Administration (OSHA)
Blaise Pascal	Joseph Bramah	pressure
Canadian Centre for Occupational Health and Safety	lock out and tag out	volume
	noncompressible	

INTRODUCTION

Modern hydraulic systems perform a wide range of jobs on mobile equipment. From earthmoving to removing trash and refuse to providing services to the disabled, mobile equipment hydraulics play a vital role in a wide range of industries. This book will limit itself to hydraulic system typically found in motor vehicle applications.

SAFETY

Safety Glasses

Most modern repair shops place a great deal of emphasis on eye safety. When hydraulic systems suffer a catastrophic failure such as a ruptured line and fitting, they will usually do so under extreme pressure. These high pressures can turn metal, rubber, and oil into high-velocity projectiles. When working on hydraulic systems, safety glasses are a must (**Figure 1-1**). If there is concern about the condition of the system, especially pressure-related problems, a ballistic face shield in addition to the safety glasses is strongly recommended.

Skin Penetration Risks

A rather unique, though very real risk when working with hydraulic systems is that of skin penetration. According to the *Occupational Safety Handbook* published by the **Occupational Safety and Health Administration (OSHA)**, pressures as low as 100 psi can force oils and other fluid through the skin (**Figure 1-2**). In addition to severe lacerations, once these oils enter the bloodstream they often prove to be highly toxic.

Never Open a Pressurized Line

In addition to the potential for eye damage and injection through the skin, a pressurized line may be all that is supporting a major component on a vehicle or mobile hydraulic system that is being repaired. As a personal anecdote, I once arrived to do a class at a city-owned repair shop in California. Only minutes before, a technician had removed a pressurized line from the cylinder on a dump truck bed. The dump truck bed was elevated at the time. The check valve he had assumed would hold the dump bed in the raised position was apparently defective. The dump bed rapidly came down and crushed him. Although he lived, he was severely injured. Never remove a pressurized line or a component from a pressurized line, pump, motor, cylinder, or any other component.

**A****B****C**

Figure 1-1 Everyone gets only a single pair of eyes. Since accidents and unexpected flying parts can occur at any time while servicing fluid power systems, safety glasses should be worn even when performing minor repairs or service.

LOCK OUT/TAG OUT

The purpose of a **lock out/tag out** program is to prevent the accidental operation or start-up of equipment while it is being diagnosed, repaired, or serviced.

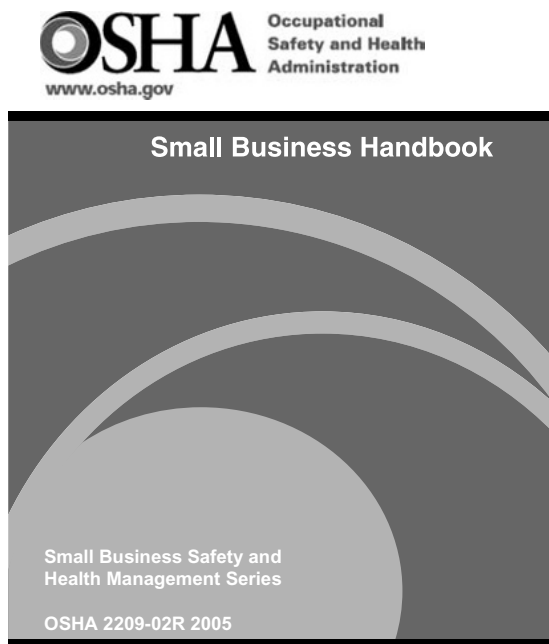


Figure 1-2 The Occupational Safety and Health Administration and the **Canadian Centre for Occupational Health and Safety** provide detailed guidelines and procedures to ensure the safety of workers. Procedures and processes are outlined and detailed in various publications of these agencies.

This will protect service technicians and property from damage.

Lock Out/Tag Out Procedures

There are usually formal procedures for lock out/tag out outlined in company employee manuals or company safety manuals. Certain basic procedures always apply (**Figure 1-3**).

Before working on, repairing, adjusting, or replacing machinery and equipment, the following procedures will be utilized to place the machinery and equipment in a neutral or zero mechanical state.

- Notify all affected employees that the machinery, equipment, or system will be out of service.
- If the machinery, equipment, or system is in operation, shut it down.
- Move switch or panel arms to “Off” or “Open” positions and close all valves or other energy isolating devices so that the energy source(s) (hydraulic pump, etc.) is disconnected or isolated from the machinery or equipment. Accumulators, lines, hoses, and all other components should be relieved of their stored pressure.
- Lock out and tag out all energy devices by using hasps, chains, and valve covers with an assigned individual lock.

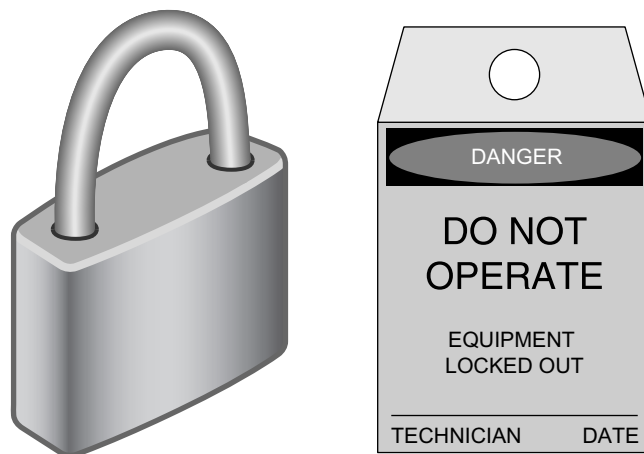


Figure 1-3 Locking out the operating controls for fluid power systems ensures that the machinery cannot be operated while maintenance or repairs are being performed. Tagging the lock and/or operating controls provides anyone attempting to operate the equipment with a warning and information about who to contact.

- After ensuring that no employee will be placed in danger, test all lock out and tag out processes by following the normal start-up procedures.
- Machinery or equipment is now locked out and tagged out.
- Should the shift change before the machinery or equipment can be restored to service, the lock out and tag out must remain. If the task is re-assigned to the next shift, those employees must perform a review of the lock out/tag out procedure with the previous technician before being allowed to transfer their lock, key, and tag.

CAUTION After testing, place the controls back in the “neutral” position.

Restoring Machinery and Equipment to Service

When the task is complete and the machinery, equipment, or process are ready for testing or returned to normal service:

- Check the area to ensure that no employee is exposed to a hazard.
- Account for all tools, repair or replace any defects, and replace all safety guards.
- Remove lock and tag. Restore energy sources. Test to ensure task has been completed satisfactorily.

Procedures Involving More Than One Technician

In the preceding steps, if more than one technician is assigned to a task requiring a lock out and tag out,

each must also place his or her own lock and tag on the energy isolating device or devices.

No lock out/tag out program should be built using the steps earlier outlined exclusively. A qualified committee that includes safety professionals should always determine and approve the exact process for any business, school, or agency.

TO GET STARTED

Like many technologies that make significant contributions to our world today, it is impossible to point to one date or person that invented the technology. Hydraulics has much of its beginning in the work of Archimedes, an inventor and scientist from the third century BCE. Some also speculate that the ancient Egyptians may have used hydraulic principles in the building of many of their structures.

Beyond such conjecture, the first patent relating to the practical use of hydraulics was issued to **Joseph Bramah** in 1795 (**Figure 1-4**). In addition to hydraulics, Bramah was also granted patents on a beverage dispenser, a flush toilet, and a pick-proof lock. All of the technologies in these patents are still in use today. His 1795 patent was for a simple, though effective, hydraulic press. The operation of that press is the principle behind nearly all modern hydraulic systems. In fact, it could be said that today's hydraulic systems are exactly what Bramah patented in 1795, but with additional controls added to make them perform in specific ways.

Bramah's invention of 1795 capitalized on a theory proposed by **Blaise Pascal**, and was in fact a refinement of an invention by Pascal. Blaise Pascal was born in 1623 and actually invented the hydraulic press that was later made practical with the addition of oil soaked leather seals by Bramah a century and a half later. Pascal's most important contribution to hydraulics was the basic operating theory. This theory states

that when there is an increase in pressure at any point in a confined fluid, there will be an increase in pressure at all other points in the fluid. His work went on to state that when a force is applied to a piston against the confined fluid, that force will create an increase in pressure within the confined fluid. That pressure change will then act upon another piston with the same change in pressure. The amount of force applied to that second piston by the change in pressure will be proportional to the size of the second piston relative to the first. Double the surface area of the second piston with respect to the first and the amount of force is doubled.

Basic Principles

NATURE OF HYDRAULICS

The term "hydraulics" derives from a Greek word that relates to water. Water and other fluids have several consistent characteristics; foremost among these in the technology of hydraulics is their **noncompressible** nature. It is the nature of liquids to maintain their volume even as pressure is increased upon them. Without this characteristic, a ship sitting on the sea would compress the water below it, the water would give way, and the ship would slip to the bottom of the sea. As it is, the water pushes back as the ship pushes down and the offsetting forces are achieved (**Figure 1-5**). Modern hydraulics takes advantage of these offsetting forces so that relatively small machines can accomplish relatively large tasks.

The noncompressibility of liquids makes them perfect for the immediate transmission of energy from one place to another. In a closed system, applying a force or setting the fluid in motion produces an immediate and equal response at all other points in the closed system. A related technology, pneumatics, is governed by a very similar set of laws and formulae,

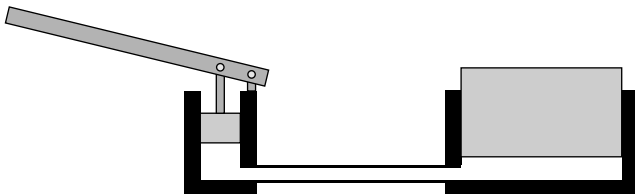


Figure 1-4 In 1795, Joseph Bramah patented a hydraulic press that worked much like the example illustrated here. A small piston, with a small amount of fluid, moved a large piston, multiplying the force many times. His original press was used by the King of England in the Tower of London to flatten paper.

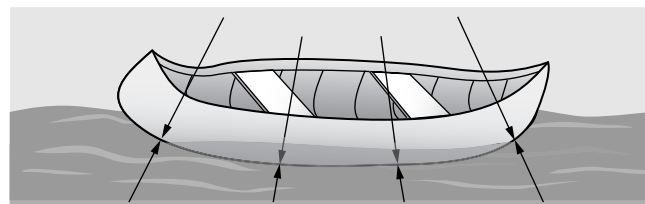


Figure 1-5 The principles of hydraulics have been known for thousands of years. The basic principle can be applied to a boat or ship simply sitting in water, where the weight of the ship applies a force against the water, and the water applies an equal force against the ship. The end result is offsetting forces combine to keep the ship afloat.

but the “springy” nature of the pressure medium, air, significantly slows the response felt at all other points in a closed system.

SOME DEFINITIONS

Force

Force is the ability to do work or cause a physical change. In a hydraulic system, we think of force as the result of applying a pressure over a given area (**Figure 1-6**). As a result, the greater the area that a given pressure is applied to, the greater the force. In accordance with that, the greater the pressure applied to a given area, the greater the force. The pound-force, or simply the pound, is actually a measurement of the force required to accelerate a mass of 453.59 grams at a rate of approximately 32.17 feet per second.

In the metric system, the equivalent to the pound is the dyne or the Newton. A dyne is a centimeter-gram-second unit of force. It is equal to the force required to accelerate a mass of one gram at a rate of one centimeter per second.

A Newton is the unit of force required to accelerate a mass of 1 kilogram at a rate of 1 meter per second. A Newton is equivalent to 100,000 dynes.

Area

Area is a measurement that describes the size of a two-dimensional face of a solid object. Area is calculated as a measurement of length, squared. In most

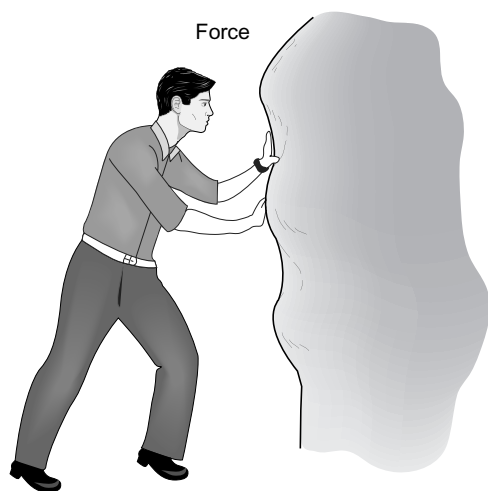


Figure 1-6 Force is the ability to do work. In a hydraulic system, we use force to transfer power from one place to another within the system. Force is a function of pressure being applied over an area.

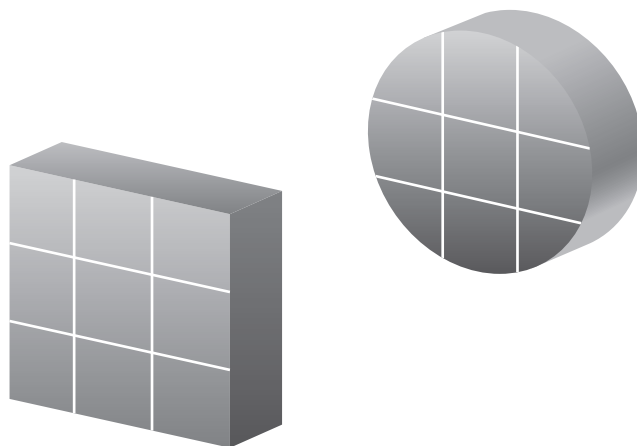


Figure 1-7 Area is a measurement of the exposed face of a surface. In the case of fluid power systems, when a fluid under pressure is in contact with a surface, a force is produced. The amount of the force is equal to the area of the surface times the pressure.

hydraulics used in North America, the measurement used to describe a surface area is square inches. This book will also include metric measurements. The common metric measurement for area is square centimeters (**Figure 1-7**).

Pressure

Pressure is a measurement of a force applied uniformly over a surface. This measurement is described in units of force per square unit of linear measurement (**Figure 1-8**). In North American applications, this measurement is usually described in pounds per square inch. The metric measurement is usually stated in *bar*. A bar is a pressure equal to 1 million dynes per square centimeter.

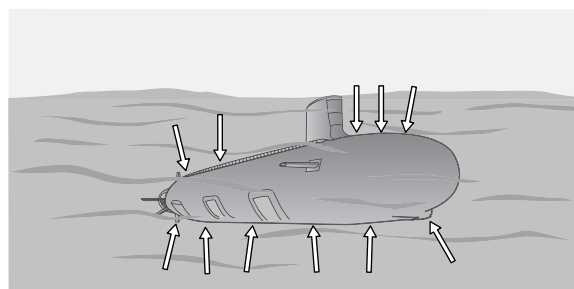


Figure 1-8 Pressure is the force being applied over a unit of area. As a submarine descends into a body of water, the water surrounds the submarine and applies a force equal in all directions. The amount of force acting on a square unit of measure, such as square inches or square centimeters, is called pressure.

Force–Area–Pressure

Perhaps the most critical concept to understand in the design, operation, and troubleshooting of hydraulic systems is the interrelationship between force, area, and pressure. Within Pascal's law there is a set of formulae that describe this relationship. This is often referred to as the FAP, or force (F)–area (A)–pressure (P) relationship.

$$F = A \times P$$

$$A = \frac{F}{P}$$

$$P = \frac{F}{A}$$

Let us say that we apply a pressure of 100 pounds per square over the surface of an object with an area of 100 square inches. The force exerted on that object, and therefore potentially transmitted by that object, is 10,000 pounds of force (**Figure 1-9**).

Let us take this a step further. Imagine applying these 100 pounds per square inch of pressure over a near cone-shaped object where the surface area of one end is 100 square inches and the surface area of the other is 1 square inch. The force applied to the 100-square-inch surface would be 10,000 pounds. If the 1-square-inch surface was against another object, it would be applying a force equal to the force applied to it on the larger side, 10,000 pounds. But since the force is spread out over an area of only 1 square inch, the pressure applied by the small side to the object it is touching is 10,000 pounds per square inch. Although the pressure is multiplied 100 fold, the force remains the same.

Using this principle, the force of a human hand on the handle of an awl or an ice pick can easily cause the

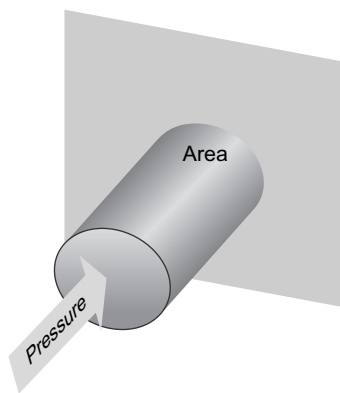


Figure 1-9 The amount of force applied to a surface is equal to the amount of pressure times the amount of area the pressure is being applied over. A pressure of 1,000 psi applied over a surface area of 1,000 square inches equals 1,000,000 pounds of force.

point to penetrate tough leather. This principle has been applied by humankind since prehistoric times. It is the basic principle behind the stone knife.

Volume–Area–Length

Area also plays a vital role in another principle. Unlike in our cone example, a modern hydraulic system depends on the movement of flow to and through cylinders, and motors through conduits, hoses, or piping (**Figure 1-10**). All of these devices are three dimensional in nature and therefore not only have area, but contain a volume. **Volume** is the capacity of a region or of a specified container expressed in cubic units. In North American measurement systems, the most common measurement is gallons, the same gallons used to measure milk, water, and other liquids. Cubic linear measurements are often used to describe volume in design and troubleshooting. The most common unit is cubic inches (in^3).

Similarly, the most common metric measurement is liters, although cubic decimeters (dm^3) and other length-related measurements are sometimes used.

Imagine a cylinder with a volume of 2 gallons. Since there is 231 cubic inches in a gallon, we might also say there are 462 cubic inches of volume in the cylinder. If the area of the surface that would be formed across the end of the circle was 12.56 inches, then the length of the cylinder must be 36.78 inches.

A PRACTICAL APPLICATION

In a more practical application, let us calculate the volume of a 6-inch cylinder with a 24-inch stroke.

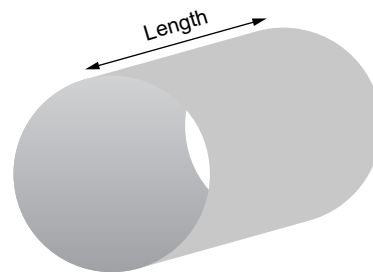


Figure 1-10 The size of the cylinder being used by an object or to actuate a device will impact the speed at which the device can operate. Volume is a measurement of the cylinder that has a direct impact on the speed of operation. Volume is calculated by multiplying the surface area times the stroke or length of movement of the piston times the surface area of the system. If the surface area is 10 square inches and the length of the stroke is 15 inches, then the volume required to stroke the piston from full retraction to full extension is 150 cubic inches.

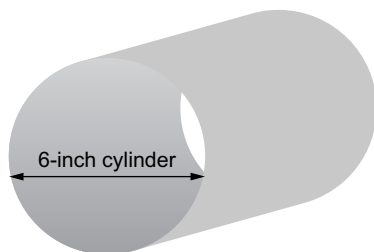


Figure 1-11 When documentation of a fluid power system refers to a 6-inch cylinder, this means that the diameter of the cylinder is 6 inches.

When a cylinder is referred to as a “6-inch” cylinder, it typically means that the diameter of the cylinder is 6 inches (**Figure 1-11**).

Volume is a function of area multiplied by length. The first thing that needs to be calculated is the cross-sectional area of the cylinder. This is done by multiplying the ratio of a circle’s diameter to its circumference, also known as Archimedes constant or pi, by the square of the radius of the cylinder, and then taking that result and multiplying it by the length (**Figure 1-12**). It sounds more difficult than it actually is. Follow these steps:

1. Measure the diameter of the cylinder. In this case, 6 inches.
2. Divide by 2 to find the radius. This would be 3 inches.
3. Multiply the result by itself. In this case, 3 times 3 equals 9. This process is called *squaring* the number.
4. Multiply the square of the radius, 9, by pi (π). In almost all hydraulic system calculations, pi is rounded to either 3.14 or 3.14159 depending on the level of accuracy required. This would give us a product of 28.26.
5. The cross-sectional area of the cylinder is thus 28.26 square inches.

Once the area is calculated, the volume is found by multiplying the area by the length (**Figure 1-13**).

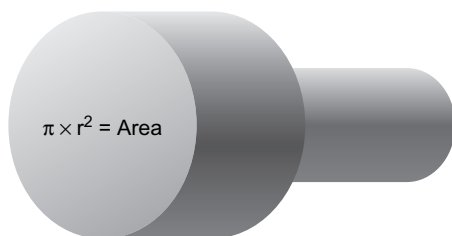


Figure 1-12 The surface area of the piston is equal to half the diameter, also known as the radius, times itself (in other words, squared), times pi (π).

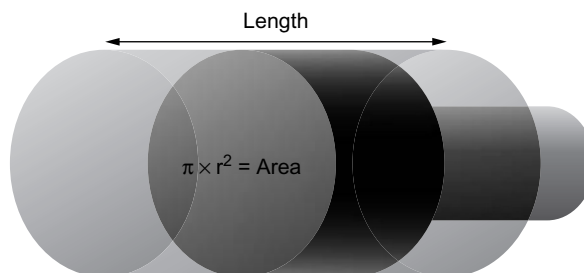


Figure 1-13 Multiplying the surface area of the piston times the length of the stroke will yield the volume of the cylinder.

The result will be in cubic inches. An area of 28.26 square inches multiplied by 24 inches equals a volume of 678.24 cubic inches.

If we want the volume measured in gallons, simply divide 678.24 by the conversion factor of 231. This will yield a calculation of 2.936 gallons. Using these calculations, if we want to move a 6-inch-diameter piston within a cylinder a distance of 24 inches, it would take nearly 3 gallons of fluid moving into the cylinder.

At this point, it is easy to become overwhelmed by the math. Designing a properly operating hydraulic system is a very math-intensive process. Although some math is required at times to get a feel for how a system should be operating, troubleshooting is generally far less dependent on math skills.

Velocity–Flow Rate–Diameter

As important as the amount of force that a hydraulic system can bring to a job is the speed at which that job can be performed. This speed factor is called velocity and it is a direct function of flow rate. Flow rate is a function of the capability of the pump and the diameter of the components, conduits, hoses, and pipes carrying the fluid (**Figure 1-14**). Flow rate is measured in gallons per minute or liters per minute. Velocity is the time it takes for a mass of fluid or a hydraulic system component to move from point A to point B. Velocity is usually measured in feet per second or meters per second.

Using our previous example of the 6-inch cylinder with a 24-inch length, we will now calculate how long it will take for the piston within the cylinder to move the full range of its stroke. The first thing we will need to know is the supply capacity of the pump supplying fluid to the system. Let us assume that the capacity is 6 gallons per minute. Knowing this flow rate, we can determine how long it should take to move the piston the full length of the cylinder. We have already determined that the fully extended cylinder will hold

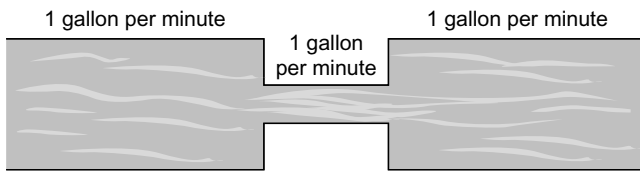


Figure 1-14 The flow rate of fluid in any given branch of a hydraulic circuit is constant throughout the branch. A restriction will cause a change in velocity of the fluid through the restriction. This is similar to a river flowing through a narrow channel. When the channel is wide, the water in the river flows leisurely along. As the channel begins to narrow, the flow rate of the water will remain a constant, but the speed of the water will increase in order to maintain that same flow rate. This is best exemplified by the rapids that are often found at the narrow points of a river channel. Anyone who has ever seen films or videos of white water rafting has seen a perfect example of this.

2.936 gallons. Dividing the extended cylinder volume by the 6-gallon-per-minute flow rate would yield a result of 0.4893 minutes or about 29.36 seconds. Although sometimes manufacturing machinery times must be calculated and monitored that accurately, this book concentrates on mobile equipment hydraulics and therefore it is acceptable to round the 0.4893 minutes to half a minute or 30 seconds.

The preceding calculations assume that whatever the pump produces can arrive at the cylinder at the same rate the pump is sending it. As we will see in subsequent chapters, this is seldom the case. The diameter of the hoses leading to and from can limit the flow rate to the cylinder. In general, the smaller the diameter, the lower the flow rate.



Figure 1-15 All the rules and laws of hydraulic systems and fluid power systems are at play even in this simple bottle jack. The user applies a small amount of work many, many times to the small piston on the side of the jack. Each time the work is applied, a small amount of fluid is moved from the small system to the large piston. Slowly, the extend side of the large piston is moved upward by each sequential movement of the small piston. The pressure applied by the small piston to the large piston is multiplied in force by the surface area of the large piston, allowing the bottle jack to move or lift very heavy loads.

Decreasing the diameter causes a decrease in flow rate, and as it causes this decrease in flow rate, another characteristic of the fluid flow called velocity will increase. As the diameter of the hose decreases, the speed of a given drop of fluid must increase in order for the flow rate to be maintained (**Figure 1-15**). This increase in speed is an increase in velocity. There will be more on that in later chapters.

Summary

Hydraulics is both an ancient science and a new technology. Like any technology, many complexities and nuances can affect the operation of a hydraulic system. In spite of that fact, all of the complexities and nuances follow a rather small number of laws and rules

and are governed by a very small set of mathematical principles. Understanding these principles, regardless of one's skill in mathematics, will make a technician efficient and skilled when troubleshooting and repairing hydraulic systems.

Review Questions

- Applying an even pressure on the large end of a cone will result in what kind of pressure at the small end of the cone?
 - A much greater pressure
 - A much smaller pressure
 - The pressure will not change
 - Only the force will change

2. When fluid flows into a cylinder, as the flow rate increases, the speed of the piston in the cylinder:
 - A. Increases.
 - B. Decreases.
 - C. Is unaffected.
 - D. Whether it increases or decreases depends on the diameter of the cylinder.
3. A pressure of 200 psi is applied to one end of a piston that has a surface area of 10 square inches. What is the total force on the piston?
 - A. 20 pounds of force
 - B. 200 pounds of force
 - C. 2,000 pounds of force
 - D. This cannot be calculated with the information provided.
4. In the preceding question, if the other end of the piston has a surface area of 100 square inches, what would be the pressure on this larger end?
 - A. 2,000 psi
 - B. 200 psi
 - C. 20 psi
 - D. 2 psi
5. If all other factors remain the same, increasing the surface area of a piston:
 - A. Tends to increase force.
 - B. Tends to decrease force.
 - C. Tends to decrease pressure (psi).
 - D. Both A and C
6. In the United States, the agency responsible for establishing guidelines related to employee safety is:
 - A. United States Safety Department.
 - B. Office of Management and Safety.
 - C. Occupational Safety and Health Administration.
 - D. No such agency exists.
7. When a submarine submerges, the water applies a pressure around the cylinder of the submarine that is:
 - A. Equal at all points around the cylinder.
 - B. Greater on the top than it is the bottom.
 - C. No pressure is applied; there is only force.
 - D. The force is equal, but the pressure changes along the length of the cylinder.
8. The lock out/tag out procedure is important:
 - A. To protect the technician from personal injury.
 - B. To protect the equipment from damage.
 - C. Both of the above
 - D. Neither of the above
9. Personal protective equipment (PPE) is extremely important in providing a safe working environment for the technician. Who is responsible for ensuring that every technician properly wears protective equipment?
 - A. The individual technician
 - B. The technician's employer
 - C. The technician's co-workers
 - D. All of the above
10. A simple hydraulic bottle jack follows all the rules of fluid power and hydraulic systems except for:
 - A. Flow, area, pressure.
 - B. Area, pressure, velocity.
 - C. Flow, velocity, area.
 - D. It follows all the rules of fluid power and hydraulic systems.

